Laboratory Study of the Diagnostic Utility of the 3C/3D line ratio in Fe XVII

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ABSTRACT

Fe XVII x-ray emission is present in a multitude of sources, such as the corona of the Sun, Capella, and Procyon. Two of the strongest lines observed in these spectra are the resonance and intercombination lines located at 15.01 and 15.26 Å, respectively. As part of the laboratory astrophysics program at the electron beam ion traps EBIT-I & EBIT-II located at the Lawrence Livermore National Laboratory we have measured this line ratio for the case where the relative abundance of Fe XVI to Fe XVII is ~ 1. Our results show that an Fe XVI innershell satellite line coincides with the intercombination line and can significantly reduce the relative intensity, R, of the resonance to intercombination line. The fact that the apparent relative intensity of the resonance and intercombination line in Fe XVII is sensitive to the strength of an Fe XVI innershell satellite, and therefore, the relative abundance of Fe XVI to Fe XVII, makes the line ratio a diagnostic of temperature, and explains the anomalously low ratios observed in the solar and stellar coronae.

1. Introduction

The L-shell line emission of Fe XVII is present over a large temperature range and is observed in the corona of the Sun and in extra-solar sources. Two of the most distinct lines observed from Fe XVII are the $1s^2 2s^2 2p^5_{1/2} 3d_{3/2} \, ^1P_1 \to 1s^2 2s^2 2p^6 \, ^1S_0$ resonance and $1s^2 2s^2 2p^5_{3/2} 3d_{5/2} \, ^3D_1 \to 1s^2 2s^2 2p^6 \, ^1S_0$ intercombination lines at 15.01 and 15.26 Å known as 3C and 3D, respectively.

Values of the relative intensity, R, of these two lines between 1.6 and 2.8 have been measured in non-flaring active regions of the solar corona. Values in the range of 2.6 to
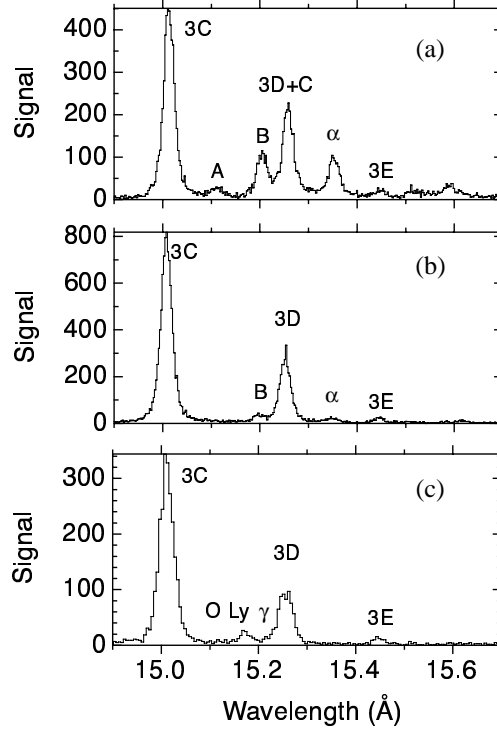
Fig. 1.— Fe L-shell spectra measured for different ionization balances: (a) very low ionization balance; (b) low ionization balance (c) standard (equilibrium) ionization balance (typical for EBIT-II) obtained by injection with the MeVVA. Lines 3C, 3D, and 3E are from Fe XVII. Lines A, B, and C are innershell satellites from Fe XVI, and line α is an Fe XV innershell satellite.

2.8 have been measured from Capella, and recently, Raassen et al. (2002) have reported a value of 1.8 from Procyon. By contrast, measurements on the LLNL electron beam ion trap EBIT-II gave an average value of 3.04 $\pm$ 0.12 for electron impact excitation (Brown et al. 1998). The EBIT-II value agrees with only some of the higher values measured in the Sun and is marginally in agreement with the Capella ratio. A second experiment conducted at EBIT-II (Brown et al. 2001) has shown that an Fe XVI innershell satellite line coincides with the Fe XVII intercombination line 3D. Figure 1 shows the results of measuring the x-ray emission between 14.9 and 15.7 Å from Fe XVI and XVII with different amounts of Fe XVI present (Brown et al. 2001). When the relative abundance of ~ 1 (figure 1a) the relative line intensity is below 2. When no Fe XVI is present, as in figure 1c, the ratio is 3. Because R is sensitive to the relative abundance of Fe XVI and Fe XVII, it is a measure of the charge balance and thus of the electron temperature.
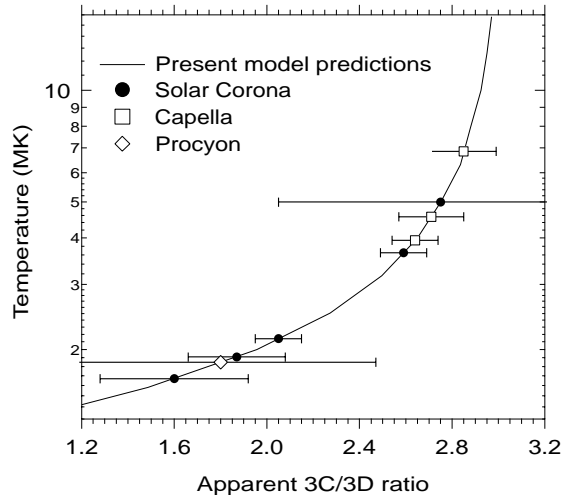
Fig. 2.— Correlation of the apparent 3C-to-3D ratio with the electron temperature. The solar points corresponding to cooler temperatures are from non-flaring active regions while the hotter solar points are from flaring active regions. The Capella data is from observations with both the LETG and the HETG on the *Chandra X-Ray Observatory*. The Procyon data is from the RGS1 on board *XMM-Newton*.

2. Discussion

The fact that an Fe XVI innershell satellite line coincides with line 3D explains the relatively low ratios measured in Capella, Procyon, and non-flaring active regions of the Sun, and can be used to predict their temperature. Figure 2 shows a plot of temperature versus R. Included are the ratios measured in the corona of the Sun, Capella, and Procyon and their predicted temperatures. We note that we do not include the value of 2.89 ± 1.8 measured by RGS2 on *XMM-Newton* (Raassen et al. 2002), because of the large error bars. However, using the value of 1.8 ± 0.7 measured by RGS1, we predict a temperature range of 1-3 MK, consistent with the values of the peak of the emission measure given by the *XMM* data.

In addition to explaining the results observed in non-terrestrial source, the line coincidence also explains the low ratios observed in other laboratory devices. Beiersdorfer et al. (2001) measured an average value of 2.48 ± 0.40 using a flat crystal Bragg spectrometer on the Princeton Large Torus tokamak. The only process available to explain the low ratio in this device is the Fe XVI line coincidence. The ratio of 2.50 ± 0.13, measured by Laming et al. (2000) in the NIST electron beam ion trap, can also be explained by the Fe XVI line coincidence. When using an electron beam ion trap to measure x-ray emission from iron charges states greater than or equal to Fe XVII, Fe XVI is present during the ionization phase

of the injection cycle, i.e, the time immediately after the injection of iron. This contamination can be avoided if only the equilibrium portion of the trapping cycle is used, i.e, the ionization phase is gated out. This is the case for the spectrum in figure 1c measured at the LLNL EBIT-II where the Fe XVI contamination is not present.

3.   Summary

In summary, we have taken advantage of the fact that an innershell satellite line from Na-like Fe XVI coincides with the intercombination line 3D in Fe XVII to predict the temperature of solar and stellar coronae. This temperature diagnostic is only one of the many line diagnostics that have become available to the astrophysical community as a result of the synergy between laboratory astrophysics programs and the high-resolution spectral data provided by the *Chandra X-ray Observatory* and *XMM-Newton.* Also, this line coincidence explains the low ratios measured in other laboratory experiments where an influential amount of Fe XVI exists.

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